Renewable and Sustainable Energy Reviews 20 (2013) 57–70

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Assessment of optimal size of anaerobic co-digestion plants: An application to cattle farms in the province of Bari (Italy)

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ARTICLE INFO

Article history:
Received 17 March 2012
Received in revised form
21 November 2012
Accepted 26 November 2012
Available online 23 December 2012

Keywords:
Biogas
Anaerobic digestion
Animal manure
Feed-in tariff

ABSTRACT

Energy production from anaerobic digestion of organic waste and dedicated digestable biomass is a promising climate change mitigation option. Over the last ten years anaerobic digestion has become established in many European countries. The plants have been developed for renewable energy generation, but also to control the emission of odors from zootechnical farms and to stabilize biomass before its agronomic use. In Italy the subsidies available for power generation from biomass have given rise to renewed interest in biogas, creating new opportunities for the agricultural and livestock sectors.

Despite of this, in Southern Italy the manure is highly dispersed over a large number of small-size cattle farms, while power generation facilities are affected by scale economies and the aggregation of input biomass is a major logistic, managing, economic and environmental drawback towards the diffusion of such technologies. In this paper, an investment decision methodology for the assessment of optimal size and feedstock mix of biogas power plants fed by cattle manure and energy crops is presented. The methodology is applied to one of the most promising basins of Puglia region, in Southern Italy, represented by the Municipalities of the Local Action Group "*Terra dei Trulli e del Barsento*", Province of Bari. The main factors influencing the profitability of these investments are assessed, with biogas power plant size ranging between 50 kW and 1 MW, and on the basis of the recently introduced feed-in tariff scheme for such plants (D.M. 6 July 2012). The results show that a high manure recovery rate, the reuse of biogas slurry and the cogeneration options are major key factor for the profitability of the investments.

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http://dx.doi.org/10.1016/j.rser.2012.11.068

1. Introduction

Anaerobic digestion (AD) is a very promising solution for the treatment of agricultural and zootechnical wastes, preventing pollution and leading to efficient energy production. In Europe, enhanced production of biogas from animal manure and other fermentable biomasses is encouraged by the European Directive for promotion of renewable energy sources [1] with mandatory implementation through National Action Plants at Member States level.

The manure produced by cattle farms might be used to produce biogas by AD processes, to be directly converted into heat and power by internal combustion engines or upgraded to biomethane and fed into the gas network. The subsidies available in Italy for biofuels (green certificates and/or feed in tariff for renewable electricity, feed in tariff for biomethane) [2,3], in agreement with EC Directives [1] are increasing the interest in the energy conversion of such animal wastes, also in combination with other residual and dedicated fermentable biomasses. Moreover, the recovery of animal manure for energy generation could facilitate the control of odor emissions and stabilize the biomass before its agronomic use. In Italy, about 500 AD biogas plants fed by manure, energy crops and/or agricultural digestable substrates are installed by 2011. The prevalent size of the plant increased from 150 to 200 kWe of 2009 to about 500 kWe of 2010, with a total installed power of about 388 MWe at end 2011.

The Province of Bari (Puglia Region, Italy) includes many cattle farms and high density of cow breeding. About 70% of these farms is located in the seven Municipalities included in the Local Action Group (LAG) "*Terra dei Trulli e del Barsento*", in the South of the Province of Bari. Despite of the high incentives available for biogas generation, the manure in Southern Italy is highly dispersed over a large number of small-size farms, so increasing the biomass transport costs. Moreover, the aggregation of several farms to feed a centralized plant presents several supply side managing issues, since the optimal operation and the consequent bankability of these projects requires reliable biomass supply chains as regards quality, quantity and delivery price. On the counterpart, biogas facilities are affected by scale economies and their global efficiency is influenced by the plant size, so that a minimum quantity of biomass feedstock should be available for a profitability of the investment. One possibility to overcome these barriers is to enlarge the biomass supply chain by co-digestion of other residual digestable biomasses (such as diary, brewery, winery, olive and other agro-industrial wastes, or organic fraction of urban wastes) but also of dedicated energy crops. In the first case, the low or even negative waste biomass supply cost makes profitable the investment, but the permitting issues can be quite complex and the final agronomic use of biogas slurry is more difficult for technical and permitting issues. In the second case, the land suitability for energy crops, the, sustainability implications of water, fertilizers consumption and whole chain energy balances, the food/animal feed vs. energy dynamics and the economics of the investment (biomass supply costs) are the main drawbacks. For these reasons, the selection of the optimal biogas plant size for a given territory and mix of feedstocks can be a complex issues, influenced by economic, technical, logistic and organizational factors. Another major barrier towards the development of biogas routes is the scarcity of reliable information for decision-makers and investors about the biomass energy potentials. In fact, except for very general data and statistics values, there is poor information about the quantity of manure and other agro-industrial by-products that could be converted into energy in a sustainable way.

In this paper, a general framework for the techno-economic assessment of biogas production from cattle manure and energy crops is proposed and applied to the case study of the seven Municipalities of the LAG Terra dei Trulli e del Barsento, in the Puglia Region. In the first part, the general approach for the selection of the optimal biogas plant is presented. In the second part, the approach is applied to the territory of investigation. In particular, the assessment of both cattle manure and dedicated energy crops potentials for biogas generation is described, by means of structured interviews with local farmers and main operators of the sector. Moreover, the profitability assessment of biogas CHP plants fed by manure and energy crops is proposed. The scenarios of only electricity generation, cogeneration of heat and power and sale of biogas slurry as fertilizer for agronomic use are considered, and the power size ranges between 50 kW and 1 MW. The aim of the research is to evaluate the optimal biogas plant size under various scenarios for the territory under study, and assess the influence of scale economies, scale vs. efficiency dynamics, supply chain costs, collection radius size and incentive levels on the optimal biogas plant size selection.

2. Optimization of biogas power plants size

Biogas power plants can be conducted at a wide range of capacities. The problem of optimal size calculation of biomass-to-energy conversion plants has been widely addressed in literature, on the basis of the trade-off between the high conversion efficiencies and economies of scale of large size plants and the low biomass collection radius, transport costs and feedstocks collection and management requirements of small size plants [4–8].

Factors such as feedstock availability and spatial distribution, terrain and road conditions, biomass transport specific costs, storage costs, existing energy infrastructures, biomass seasonality issues, conversion plant scale factors and efficiencies influence this optimization problem. Logistic aspects are particularly relevant when low energy density and highly dispersed feedstocks are used, such as in the case of cattle manure. Moreover, small

scale plants can facilitate the use of excess heat generated, that can match local loads, if a cogeneration configuration is selected. In [9,10], two generic analytical frameworks are proposed, to calculate the optimal conversion plant size for biogas plants. A specific analysis of the influence of plant size on the biogas and electricity production costs for silage maize biogas plants in the range of 25–2000 kWe is proposed in [11], while the profitability of cattle manure biogas plants with different sizes in Ontario is proposed in [12]. In [13], the cost of pipelining manure from beef cattle feedstocks and digestate from an AD plant as an alternative to truck transport is also explored, considering the influence of slurry concentrations and evaluating the minimum plant size for a profitability of pipeline systems. The influence of plant size and biomass/digestate logistics of transport on the environmental performances is also addressed in literature [14]. The scale optimization problem is often related to the selection of best plant location over the territory [15,16], and for this purpose in [17,18] GIS-based tools are proposed for the assessment of manure potentials, logistic issues and for identification of biogas suitable territorial clusters and plants locations.

Biomass transport modelling is essential to evaluate the related costs and optimize bioenergy plant size. Various typologies of biomass transport models are available in the literature. A first type is a simple continuous model [5,19], which is suitable for idealized situations; a second type is a discrete model with defined grid road systems [4,20]; a third type is a complete discrete model incorporating GIS [10,21]. In the first and second type of models, road tortuosity is generally based on assumptions without carrying out road system evaluations. In the last type, the road network is rasterised and then continuous grids of distance and transportation costs to the plant sites are computed using functions of Euclidean distance and allocation. Moreover, in case of on-farm biomass transport, previous studies [8] show that the haulage cost is also dictated by farm landscape attributes and infrastructure.

In addition, the legislative framework could be another key factor influencing the pant size selection; in fact, in several Countries, subsiding mechanisms and permitting issues are dependent on the power plant size. It is the case of Italy, where feed-in tariffs, available for power plants up to 1 MWe, are differentiated on the basis of the plant size, while simplified permitting procedures are reserved to cogeneration plants and power plants up to 250 kWe [2,22,23].

3. The proposed methodology

The approach is schematically shown in Fig. 1. The basic features of the approach are as follows:

- It uses structured interviews with cattle breeding operators and collection of statistic and literature data in order to estimate the quantities of cattle manure and locally grown energy crops (at cattle farm level) available for anaerobic digestion;
- On the basis of (i) the biomass potentials assessment, (ii) existing data on biomass feedstocks characteristics and (iii) anaerobic digestion and CHP plants performances, estimates of mass and energy balances for the different streams of the biofuel plants are produced;
- The economic performances of the investments for various plant sizes are assessed on the basis of: (i) investment and operation al costs, (ii) subsidies available and (iii) market prices for end-products (heat, electricity, biogas slurry).

In the following, the methodology is detailed.

3.1. Mass and energy balance

The gross electrical power $P_{e,i}$ (kWe) of a biogas plant of size i can be expressed as a function of the input biomass according to the formula:

$$P_{e,i} = \left[(Q_{m,i} \times TS_m \times VS_m \times Y_m \times (1-l_m)) + (Q_{ec,i} \times TS_{ec} \times VS_{ec} \times Y_{ec} \times (1-l_{ec})) \right] \frac{CH_4 \times LHV \times \eta_{e,i}}{h_i} \quad (1)$$

where $Q_{m,i}$ (t/yr) and $Q_{ec,i}$ (t/yr) are respectively the annual manure and energy crops consumption of the biogas power plant, TS (%),VS (%), Y (N m^3/t) and l (%) are respectively the total solids percentage, volatile solids percentage, biogas yield of the volatile percentage and storage losses of the biomass; CH_4 (%) is the percentage of natural gas in the biogas and LHV (kW h/N m^3)

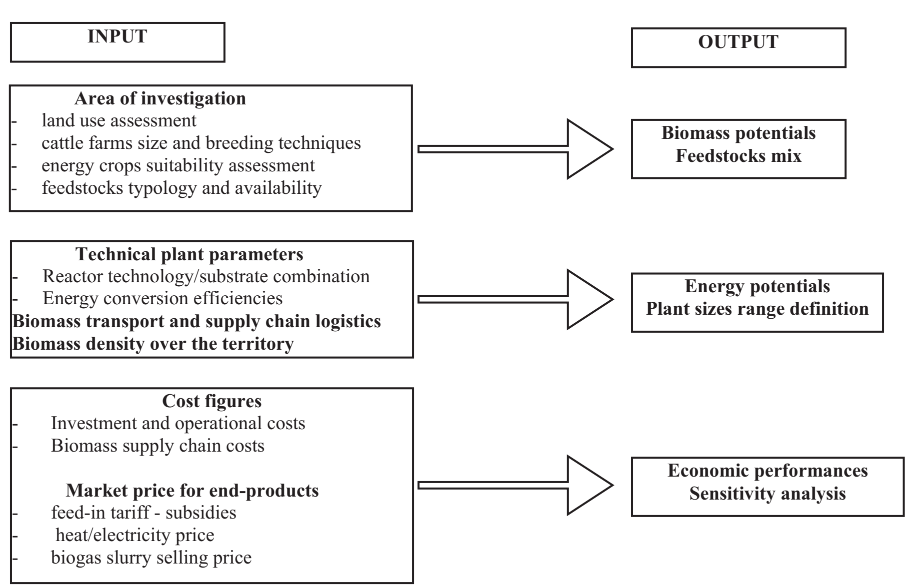

Fig. 1. Structure of the proposed approach for biogas plant techno-economic feasibility assessment indicating input and output streams.

is the low heating value of natural gas; $\eta_{e,i}$ is the electric efficiency of the power plant and h_i the annual operating hours (h/yr).

The hypothesis of the model is to grow energy crops in the cattle farm's sowable land in order to integrate the manure feedstock. The quantity $Q_{ec,i}$ can be expressed according to the formula:

$$Q_{ec,i} = \beta \times n_i \times UAS_M \times Y^C \tag{2}$$

where β (%) is the percentage of sowable land of the cattle farms converted to energy crops; n_i is the number of cattle farms required to produce the biomass (manure and energy crops) to feed the biogas plant; Y^C is the energy crop yield (t/ha yr); UAS_M is the average sowable land per cattle farm (ha/farm).

The number of cattle farms n_i is calculated as:

$$n_i = \frac{ABU_i}{ABU_M} \tag{3}$$

where ABU_M is the average number of Adult Bovine Units (ABUs) per cattle farm, and ABU_i is the number of adult bovine units required to produce $Q_{m,i}$, that is calculated as follows:

$$ABU_i = \frac{\alpha \times W_{ABU} \times Q_{m,i}}{X_m} \tag{4}$$

where α (%),W_{ABU} (t/ABU) and X_m (t manure/t living weight year) are, respectively, the percentage of manure that can be recovered for anaerobic digestion, the living weight per ABU and the annual quantity of cattle manure produced per bovine living weight. Equation (1) can thus be written as:

$$P_{e,i} = Q_{m,i}\left[(TS_m \times VS_m \times Y_m \times (1-l_m)) + \left(\frac{\beta_{ec} \times \alpha \times W_{ABU} \times UAS_M \times Y^C}{ABU_M \times X_m} \times TS_{ec} \times VS_{ec} \times Y_{ec} \times (1-l_{ec})\right)\right]\frac{\mathrm{CH_4} \times LHV \times \eta_{e,i}}{h_i} \tag{5}$$

3.2. Collection radius assessment

It is assumed that the supply area is represented by a series of concentric circles featuring a constant proportion of cattle manure and energy crops. The radius of the area of supply r_i (km) can thus be expressed as:

$$r_i = \sqrt{\frac{ABU_i}{\pi \times \rho_{ABU}}} \tag{6}$$

where ρ_{ABU} is the density of ABU over the territory (ABU/km^2).

The average haul distance d_i (km) between the biogas plant at the center of a circle and the biomass can be calculated introducing the tortuosity factor τ, that takes in account the fact that the road connecting a farm to the bioenergy plant is not straight; the following expression can be used [19]:

$$d_i = \frac{2}{3} \times r_i \times \tau \tag{7}$$

3.3. Costs assessment

The annual plant cost C_i is calculated according to Eqs. (8) and (9), being f_a the annuity factor, L (yr) is the economic life of the plant, y (yr)$^{-1}$ is the effective discount rate, C^I (kEur), C^B (kEur/yr) and $C^{O\&M}$ (kEur/yr) respectively the turn-key plant cost, the total biomass cost and the operational cost.

$$C_i = f_a \times C_i^I + C_i^B + C_i^{O\&M} \tag{8}$$

$$f_a = \left[\frac{y \cdot (1+y)^L}{(1+y)^L - 1}\right] \tag{9}$$

The turn-key cost is expressed according to Eq. (10), being C^{plant}, C^{storage} and C^{heat} (kEur), respectively, the investment cost in case of only cattle manure consumption, the further biomass storage investment cost (which is required in case of energy crop feedstock because of its seasonality) and the costs for cogeneration and heat delivery to the loads (in case of CHP option). C^{storage} is calculated according to Eq. (11), where ρ_{ec} (t/m^3), c^{storage} (kEur/m^2), h_s (m) and t_{ec} (days) represent respectively the energy crops bulk density, the unitary storage cost, the height of the closed storage tanks and the duration of the energy crop harvesting and plant delivery period. In fact, the longer is the harvesting and biomass supply period and the lower is the storage capacity requirement.

$$C_i^I = C_i^{\text{storage}} + C_i^{\text{plant}} + C_i^{\text{heat}} \tag{10}$$

$$C_i^{\text{storage}} = Q_{ec,i} \times \frac{c^{\text{storage}}}{\rho_{ec} \times h_S} \times \left(1 - \frac{t_{ec}}{365}\right) \tag{11}$$

The total biomass cost is calculated by the unitary biomass purchase price C^P (kEur/t), the loading and unloading cost C^L (kEur/t), and the transport cost, where c_{tr} (kEur/m^3 km) represents the biomass road transport rate and the factor 2 takes in account a necessary round trip, as reported in Eq. (12):

$$C_i^B = Q_{m,i} \times \left(C_m^P + C_m^L + 2 \times d_i \times \frac{c_{tr}}{\rho_m}\right) + Q_{ec,i} \times \left(C_{ec}^P + C_{ec}^L + 2 \times d_i \times \frac{c_{tr}}{\rho_{ec}}\right) \tag{12}$$

This formulation assumes a biomass road transport operated by an independent third-part transport service provider, with a centralized operation of the supply chain and consequently a constant biomass road transport rate. With these assumptions, the biogas slurry produced by the anaerobic digestion could be transported back to the fields by the same trucks that transport the manure to the plant, with no additional transport costs.

The operation and maintenance cost is the sum of administrative costs C_{adm} (kEur/yr), labour costs (being n_p the number of workers and c_p their average unitary annual salary) and facility management costs. These costs include planned and unplanned maintenance service, commonly subject to a "guaranteed performance" agreement with the manufacturer, and are calculated as a function of the electricity sold to the grid by the global service factor γ (kEur/kW h), being l_e (%) the percentage of electrical auto consumption of the plant.

$$C_i^{O\&M} = \gamma \times (P_{e,i} \times h_i \times (1-l_e)) + n_p \times c_p + C_{adm} \tag{13}$$

The levelized cost of electricity LCE (Eur/MW h), in case of only electricity generation, is calculated as:

$$LCE_i = \frac{10^6 \times C_i}{P_{e,i} \times h_i \times (1-l_e)}. \tag{14}$$

3.4. Profitability assessment

The annual income R_i (kEur/yr) from the biogas plant operation is calculated as:

$$R_i = 10^{-6} \times h_i \times \left(P_{e,i} \times (1-l_e) \times EP + P_{t,i} \times f_u \times TP\right) + 10^{-3} \times D_i \times DP \tag{15}$$

where EP (Eur/MW h$_e$), TP (Eur/MW h$_t$), and DP (Eur/t biogas slurry) represent the electricity, thermal energy and biogas slurry selling prices and f_u (%) is the thermal energy utilization factor,

Table 1
Land use for the area of study. Elaboration data ISTAT 2000 (ha).

	Alberobello	Castellana Grotte	Gioia del Colle	Noci	Putignano	Sammichele	Turi	Total	%	Province of Bari	% of Province
Total surface	**3,631**	**6,304**	**16,689**	**12,778**	**8,072**	**2,221**	**6,108**	**55,803**	**100%**	**374,159**	**15%**
Agricultural surface	3,174	5,933	14,955	10,005	6,902	2,151	5,987	49,106	88%	350,873	14%
UAS	**3,129**	**5,848**	**14,839**	**9,919**	**6,802**	**2,132**	**5,852**	**48,521**	**87%**	**344,109**	**14%**
Sowable land	**1,308**	**1,117**	**10,750**	**8,474**	**4,211**	**363**	**1,023**	**27,246**	**49%**	**145,508**	**19%**

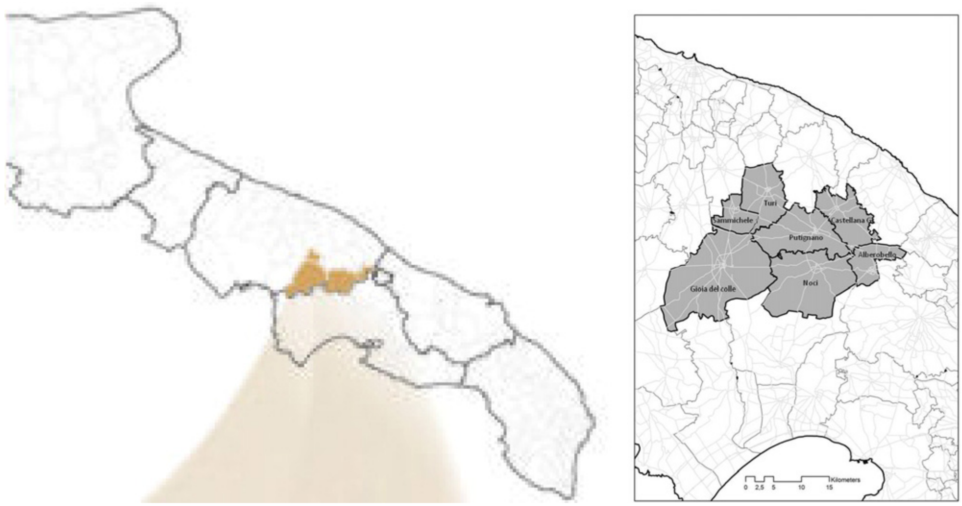

Fig. 2. Map of the selected area of study.

that is dependent on the typology of thermal load to be served in case of cogeneration. The thermal power $P_{t,i}$ (kW) is calculated according to Eq. (16), being $\eta_{t,i}$ the thermal plant efficiency. Finally, the biogas slurry D_i (t/yr) is given by Eq. (17), being D_m and D_{ec} the percentage of slurry produced by the different substrates.

$$P_{t,i} = P_{e,i}\frac{\eta_{t,i}}{\eta_{e,i}} \tag{16}$$

$$D_i = Q_{m,i} \times D_m + Q_{ec,i} \times D_{ec} \tag{17}$$

The economic assessment is carried out before tax and with no equity on investment. The Net present value (*NPV*, kEur), and the internal rate of return (*IRR*, %) are calculated according to Eqs. (18) and (19):

$$NPV_i = -C_i^I + \sum_{t=1}^{L}\frac{\left(R_{i,t} - C_{i,t}^B - C_{i,t}^{O\&M}\right)}{(1-y)^t} \tag{18}$$

$$0 = -C_i^I + \sum_{t=1}^{L}\frac{\left(R_{i,t} - C_{i,t}^B - C_{i,t}^{O\&M}\right)}{(1-IRR_i)^t} \tag{19}$$

The advantage of *NPV* is its additiviness, which means that NPVs of different projects can be summed up and the total benefits from the implementation of various investments can be quantified. The advantage of *IRR* is that, unlike *NPV*, it allows projects of vastly different size to be easily compared.

4. Area under investigation

4.1. Land use

The area under investigation includes the seven Municipalities of Table 1 and Fig. 2, that established in 2008 the Local Action Group (LAG) "*Terra dei Trulli e del Barsento*". LAGs are made up of public and private partners from the rural territory, including representatives from different socio-economic sectors, and receive financial assistance to implement local development strategies, by awarding grants to local projects.

In Table 1 the land use of these Municipalities and the useful agricultural surface (UAS) are reported, as results from [24]. The total surface is about 55,000 ha (15% of the total surface of Province of Bari). About one half of this surface is covered by sewage crops, of which about one half is dedicated to fodder for animal breeding.

4.2. Cattle farms typologies

The assessment is related to the cattle breeding farms. These farms represent the majority of the zootechnical sector in the area under investigation [25,26]. In Table 2, the number and typology of cattle farms are reported, as resulting from the statistic data of the Breeding Association of the Province of Bari. The number of ABU is calculated assuming that 60% of the bovine are adult and the remaining have a weight of 14% respect to an adult. The UAS for each farm is represented by the cattle farm's land dedicated to sewage, mainly for animal fodder. The ratio ABU/UAS is thus indicative of the space available for each bovine (dedicated to fodder production or grazing, and that could be partially converted to energy cropping). An overall of 774 farms is assessed, with a total of 25,000 ABUs. The value ABU_M for the whole area of study is 32.2 ABU/farm. The highest value is in the Municipality of Gioia del Colle (38.1 ABU/farm), which accounts for about 38% of the farms of the investigation area. In Table 2, the number of farms, ABU_M, UAS_M and ρ_{ABU} for each Municipality and for the whole area are reported. The average ABU/UAS increases with the size of the farm, and most of the farms present less than 40 ABU. In Fig. 3 the number of farms in each interval of ABU/farm are reported, showing that most of the farms have less than 50 ABUs.

Table 2
Number and typology of cattle farms in the area of study (author's elaboration on data from Breeding Association of Province of Bari, 2008).

	Turi	Castellana	Putignano	Gioia	Alberobello	Noci	Sammichele	Total area	Province of Bari	% LAG
Number of cattle farms	33	44	146	246	31	266	8	**774**	1,135	68
Number of ABUs	727	983	4,827	9.384	840	7,977	196	**24,935**	35,395	70
% ABU of total area	3	4	19	38	3	32	1	**100**		
ABU per farm (ABU_M)	22.0	22.3	33.1	38.1	27.1	30.0	24.5	**32.2**	31.2	
UAS per farm (UAS_M)	9.53	14.61	19.68	23.55	18.57	21.12	18.16	19.64		
ABU density (ρ_{ABU}	11.90	15.60	59.80	56.23	23.14	62.43	8.83	44.68		

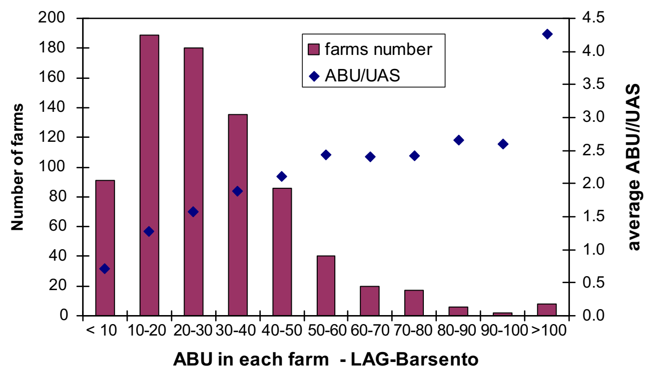

Fig. 3. Distribution of number of farms and average *ABU/UAS* ratio as a function of number of *ABU* per farm in the area of study.

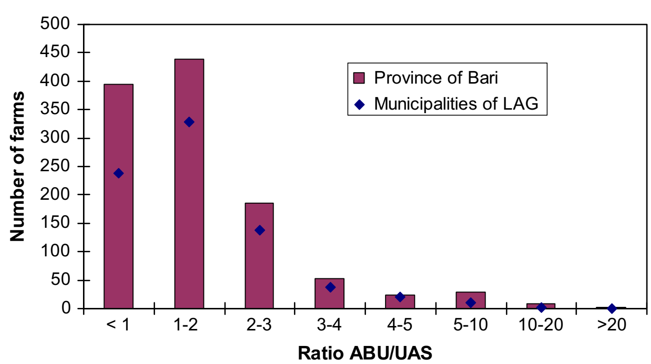

Fig. 4. Distribution of farms as a function of the *ABU/UAS* ratio for the area of study and Province of Bari.

In Fig. 4, the distribution of farms in each interval of ABU/UAS ratio is reported for the area of investigation and the whole Province of Bari. Most of the farms present a ratio ABU/UAS lower than 3, with an average value of 1.64.

5. Application: Feedstocks and energy potentials assessment

5.1. Cattle manure potentials

The feedstocks considered in this research are cattle manure and herbaceous energy crops suitable for the area of investigation. The cattle manure potentials and characteristics are strictly related to the breeding typologies and their nutritional composition. In the area of study, the cattle farms are dedicated to the milk production. Most of them adopt a free-type breeding, in which the bovines graze into the agricultural areas of farm and stand in the cowshed during the night or for milking. In this case, the animal manure is also utilized for fertilizing the pastures of agricultural areas of farms. In this type of cow-breeding the dung is prevalently dispersed, even if the use of straw litter increases the quantity of livestock available and improves its quality for anaerobic digestion. On the contrary, in the case of stall breeding, the bovines remain into a specific and organized area of farm, and the animal manure is almost completely available for an alternative utilization by gathering the waste in storage structures, even if the use of water for cleaning purposes determines large amounts of sewage. This sewage has lower energy content but can be easily handled and pumped into a digester. Moreover, the quality of the biogas slurry (digestate) produced by the anaerobic digestion and potentially useful as fertilizer, is improved when using manure instead of sewage [27]. The main parameters for the assessment of the manure potentials are reported in Table 3. They are taken from literature data [28–32] and personal communications with experts of the Breeding Association of the Province of Bari. In the proposed assessment, only the cattle manure (solid waste) is considered, representing about 90% in weight of the overall animal waste, while the sewage (liquid waste) is neglected having low energy density. In Table 3, the estimates of the "optimistic" and the BAU (business as usual) manure availability are reported, In particular, the BAU availability represents the quantity of cattle manure that is currently recovered with the adopted breeding techniques (free stalling) in the area under study. It is obtained as an average from structured interviews to 50 representative farms of the area of study. The max/min values were excluded from the average while the standard deviation of the data resulted 1.15. The optimistic scenario is defined according to author estimates of maximum manure recovery rates based on interviews with cattle breeding operators, while literature data [27,33] report recovery percentages in the range of 50%. Higher manure recovery rates would require major changes in the breeding techniques, with investment costs and different farm's organization structure; however, further insights into these major changes are out of the aims of this research.

Table 3
Assumptions for cattle manure potentials assessment.

Parameter	Value	Unit
ABU living weight (W_{ABU})	0.6	t living weight/ABU
Daily manure production per living weight X_m	0.072	t/t living weight/day
Annual manure produced	15.77	t/ABU/yr
Max manure availability (optimistic scenario) (60% total) α	**9.46**	t/ABU/yr
BAU manure availability (26% total)	4.10	t/ABU/yr

5.2. Energy crops potentials

The selection of energy crop species and its yield estimate is a task widely addressed in literature, by means of land suitability assessment methodologies [34,35], and including agronomic, pedo-climatic, economic, technological, environmental factors.

Several researches on energy crops potentials have been focused on Southern Mediterranean Regions [36–39], and other researches are specifically focused on energy crops for anaerobic fermentation processes [40–42] and co-digestion with manure [43]. Researches carried out in Puglia region [44,45] report a range of energy crops suitable for energy conversion in various processes, including anaerobic digestion. From an agronomic point of view, the energy crops alternatives for the selected area are as follows:

- Annual herbaceous summer crops (corn or sorghum silage) which present high yields but high water demand, often not compatible with the water scarcity of several areas of the Puglia Region territory [46]. In this case, drought resistant crops (such as sorghum) should be preferred, and the profitability of irrigation aid to increase the production yield should be evaluated case to case.
- Annual herbaceous winter crops (wheat, triticale, or brassicaceae crops in rotation with cereals); in this case, the main advantages are the drought resistance and the low energy inputs, while on the counterpart a lower yield is experienced in comparison to summer crops.
- Perennial herbaceous crops (panicul virgatum, miscanthus, arundo donax); in this case, the low production costs and the low agronomic and water input requirements make these crops promising; one of the main drawbacks is the land deployment for several years (about 8–10 yr), other than the costs for rhizomes propagation (expecially for miscanthus and arundo donax [47]).

On the basis of the previous considerations, the triticale has been selected as input feedstock for co-digestion, since this typology of winter crop presents a good suitability for the area of study with low water and fertilizer inputs, as results from its crop pedoclimatic requirements [48,49] and the territory characteristics [50]. This crop is already grown for silage fodder in several cattle farms of the area, and the hypothesis is to grow the crop in the same cattle farm's land and harvest it at "grain in the milk stage" to "grain in the dough stage" according to best practices [40]. For the potentials assessment a yield Y^C of 30 t/ha yr with 35% moisture content is assumed, according to data provided by farmers, while literature data [40,41,51] report yields in the range of 28–45 t/ha yr on the basis of climate conditions. Moreover, two scenarios of energy crops penetration are assumed, with an annual percentage of 10% and 30% of farm's sowable land converted to energy cropping, allowing in both cases a sustainable crop rotation [40]. Further options such as annual inter-cropping have been also proposed in literature [51] and could increase the biomass potentials for anaerobic digestion, even if not considered in this application.

5.3. Biogas production

The methane yield of the organic substrate is commonly evaluated by means of the biochemical methane potential (BMP) batch tests. Several batch methods have been proposed in literature, and in [52] the researches on the influence of different parameters of BMP determination are reviewed, including an extensive literature on methane yields of substrates and a description of the various experimental procedures used. However, the batch tests only show the potential methane yield for a given substrate, while in continuous anaerobic digestion processes these results may differ significantly, being affected by factors such as the process temperature, pH, toxicity and typology of substrate, mix of feedstock, digester sizing, residence time. In the following, a continuous dry thermophilic digestion process is assumed, which is suitable for feedstock with dry matter in the range 20–45%, such as in the proposed case. Several anaerobic digestion plants with this technology have been developed over the years [53–58]. The main advantages of dry fermentation are that the volumes of the digesters are minimised, the thermophilic operation (50–55 °C) is favoured, due to the lower thermal energy needed to heat up small volumes and concentrated (higher density) feedstocks, less intensive mixing is needed inside the digester, which leads to the reduction of energy autoconsumption, and infrastructure/logistic costs for the feedstock supply are reduced due to the increased bulk density. The main assumptions for the energy potential assessment are reported in Table 4. The biogas yield figures available from literature range between 300 N m^3/t and 400 N m^3/t VS for cattle manure [59,60] and between 450 N m^3/t and 550 N m^3/t VS for triticale [61,62], with an average reduction of 20% on respect to batch tests. Moreover, data provided by selected manufacturers of dry fermentation plants fed by cattle manure and energy crops [63–65] have been also taken in account. The data of Table 4 assume storage losses for silage triticale of 10%, as resulting from literature data [66,67], and no storage losses for the manure. The percentage of methane in biogas is 54%, and the LHV of methane is 10 kW h/N m^3.

5.4. Plant sizes selection

Five plant sizes are selected, respectively of 50 kW, 125 kW, 250 kW, 500 kW and 1 MWe. The plants sizes are selected on the basis of: (i) the average dimension and typology of cattle farms over the territory, that influence the biomass density, transport costs and supply chain managing logistics; (ii) the national legislative framework and incentives available; (iii) the technical and economic plants data available from manufacturers and from literature.

5.5. Plant configuration and energy production

In Table 5, the main technical parameters for the selected plant configurations are summarized. Operating hours and power plant efficiencies are assumed on the basis of manufacturers data [63–65], literature data [11,14,68] and reviews from similar biogas plants in operation in Italy [69,70]. In the scenario of cogeneration, the two hypotheses of agro-industrial heat demand (C-i) and residential heat demand (C-r) are considered. In the first case, the heat utilization factor f_u of 70% is assumed, while the remaining 25–30% of heat generated by the plant is commonly auto-consumed by the digestion process; it is the case, for instance, of dairy processing firms, which are often coupled to cattle farms, where low temperature (90–110 °C) heat is required

Table 4
Parameters for the energy potentials assessment.

Parameter	Manure	Herbaceous energy crop (triticale)	Unit
Total solid (TS)	0.25	0.35	% biomass
Volatile solid (VS)	0.75	0.95	% TS
Biogas yield (Y)	350	500	N m^3/t VS

Table 5
Electric efficiency and operating hours for the selected biogas power plant sizes.

Parameter	50 kW	125 kW	250 kWe	500 kWe	1 MWe
Electric efficiency η_e (%)	29.9	32.1	**33.8**	35.5	37.1
Operating hours h (h/yr)	7500	7500	**7800**	7800	8000

with a constant demand pattern. In the second case, a heat utilization factor of 25% is assumed, corresponding to an average of 1800 h/yr of heat demand. The plant autoconsumption is assumed of 6% and the thermal efficiency of 45% for the whole size range. The nitrogen, phosphorous and potassium content in the biogas slurry is reported in Table 6, according to literature data [71–73]. This product could be further treated by decanter (high speed centrifuge) or screw-press technology [74,75] for separation solid–liquid. Solid fraction can also be composted for approximately 60 days or alternatively dried with hot air supplied from the CHP plant, for applications as substitute of chemical fertilizer, enhancing its transportation efficiency. The liquid fraction can be recirculated in the AD process, spread out to the fields, or disposed in sewage treatment plant. However, in this study, no digestate treatment is considered, and the option of direct spread out to the field is considered.

6. Application: Economic assessment

6.1. Investment and operational costs

The investment cost figures for biogas plants vary extremely, on the basis of the technology and the various equipments included, especially what concerns pre-treatment, storage and handling modules of different input feedstocks. Moreover, investment cost figures often mean different things to plant owners and to equipment suppliers, depending on the limits and boundaries of the equipment and services offered. For this reason, literature data available for biogas power plant investment costs at different sizes are affected by variations of 20–30% or more [11,12,54,61,68,69,76,77]. In this study, all investment cost items have been incorporated in the turn-key-cost, including the costs of land and basic equipment plus costs for erection, piping, instrumentation, electrical works, civil works, buildings, engineering, management, commissioning, contingency and interest during construction. Based on real market values taken from technology manufacturers quotations [63–65] the investment cost figures for the selected biogas plant typologies are summarized in Table 7. The storage costs for energy crops co-digestion are calculated assuming biomass density ρ_{ec} of 0.70 t/m^3, storage tank height h_s of 3 m, 30 days of biomass supply duration t_{ec} and specific storage cost of 60 Eur/m^2. The further cogeneration case includes the heat distribution costs, and in particular district heating networks for larger plants (3 km, 2 km and 1 km, respectively, for 1 MWe, 500 kW and 250 kWe size) and only heat exchanger costs for small plants (50 kW and 125 kW) where a local thermal energy demand is considered (no district heating network).

Table 6
Characteristics of digestate.

Parameter	Value
% Nitrogen/TS in manure	1.6
% Nitrogen/TS in energy crop	1.2
% Phosphorus/TS in the manure and energy crop	0.5
% Potassium/TS in manure and energy crop	0.7

The operational costs are calculated assuming a 'global maintenance' cost γ of 32 Eur/MW h, according to technology contractors data [64,65]. In several real case studies, this maintenance cost includes a 'guaranteed performance' in terms of minimum annual electricity delivered to the grid and subject to some operational restrictions (i.e., biomass chemical–physical properties within the range provided by the manufacturer). Moreover, an average labour cost of 40 kEur/person year and administrative-insurance costs equal to 1,2% of investment cost are assumed. Respectively two and one full time workers are considered to operate the 1 MW and 500 kW plants, while in the case of smaller scale plants part-time workers are considered, since it is assumed the hypothesis of biogas plants located at the premises of "anchor" cattle farms where a greater quantity of biomass is available. In this case, the cattle farmers could operate the plant reducing the labour costs [12].

The biomass supply costs represent the greater percentage of the plant operational costs. The cattle manure supply costs is composed by the transport cost, purchase cost and loading–unloading cost. The cattle manure commonly has a purchase price equal to zero, and it is particularly true when the biogas plant owner and the cattle farmer are the same operator; moreover, this by-product could even present a negative cost, in case of local discharge problems. Despite of this, in this study the manure purchase cost is assumed 3 Eur/t at the cattle farm, as this price could encourage farmers to recover the manure for anaerobic digestion, and this price equals to an average remuneration for the cattle manure of 1000 Eur/farm year (assuming 33 ABU/farm as reported in the previous section). A specific transport cost of 0.35 Eur/m^3 km is assumed, while literature data [8,10,11] report costs in the range of 0.25–0.50 Eur/m^3 km. This hypothesis is based on manure density of 0.7 t/m^3 and the use of trucks with capacity of 5 t and a transport distance up to 30 km. The loading–unloading costs are of 1 Eur/t. The average haul distance d_i is calculated for each plant size as described in Eqs. (6) and (7). The tortuosity factor, calculated as the average value of the ratio road distance/linear distance between each Municipality (by means of detailed road maps) results of 1.27. However, we assume that the biogas plants are located in periurban or agricultural areas, at the premises of some of the greatest cattle farms, where the road density is lower and the tortuosity higher. In agreement with literature values for this kind of territory [6,8,62,78], the tortuosity factor has been increased of 30%, assuming a value of 1.65. The triticale supply cost is assumed 30 Eur/t including loading–unloading costs; it is considered a cost of 900 Eur/ha for cultivation, harvesting and loading, according to interviews with local farmers and literature data [79,80]. The energy crops transport costs are calculated as in the case of cattle manure.

6.2. Assumptions for financial appraisal of investments and scenarios definition

The following hypotheses are assumed for the financial appraisal of the investments:

– Lifetime of investment L of 20 years (equivalent to the duration of the feed-in tariff) and effective discount rate y of

Table 7
Investment costs for the biogas power plants.

Investment costs	50 kW	125 kW	250 kW	500 kW	1 MW
Specific investment cost C^{plant} (kEur/MW)	5530	4300	**3900**	3700	3600
Further investment cost for cogeneration and district heating C^{heat} (kEur)	50	100	**200**	300	400

8% (which is the average value assumed by financing institutions for these typologies of investments);
- No decommissioning costs;
- O&M costs and cash flows constant during the plant lifetime;
- Debt/equity ratio of 100% (no equity) and depreciation of investment costs spread over the whole lifetime of the plants;
- Taxation, excises VAT and municipal rates not included in the economic indices assessment;
- No capital grants;
- Feed-in tariff constant over the lifetime of the plant, differentiated according to plant size and configuration according to Italian biogas subsidy schemes [3].

The economic assessment is carried out considering, for each plant size and feedstock supply mix, the scenarios of only electricity sale (A), electricity and biogas slurry sale (B), sale of heat and electricity for agro-industrial and residential loads (C-i and C-r) and sale of heat (agro-industrial), biogas slurry and electricity (D).

The electricity feed-in tariffs *EP* for various plant sizes and scenarios are reported in Table 8. In particular, the case of biomass by-products digestion with percentage in weight of energy crops co-digestion no higher that 30% is assumed. Moreover, the bonus of 30 Eur/MW h for low air emission levels, of 30 Eur/MW h for recovery of at least 60% of nitrogen from biogas slurry (case B and D), of 40 Eur/MW h for high efficiency cogeneration with district heating (case C and D and size of 250 kWe or higher) and of 10 Eur/MW h for high efficiency cogeneration (case C and D and size of 125 kWe or lower).

These feed-in tariffs include both the incentive for renewable energy and the remuneration of the electricity sold to the grid. The thermal energy selling price of the CHP plants *TP* is assumed 40 or 75 Eur/MW h, respectively, in the case of agro-industrial and residential cogeneration (corresponding to an avoided cost of natural gas of 0.35 Eur/m^3 and 0.7 Eur/m^3, respectively). The selling price of nitrogen, potassium (P_2O_5) and phosphorus (K_2O) contained into the biogas slurry, and that can have applications as fertilizer for agronomic use, are assumed respectively of 600 Eur/t, 450 Eur/t and 420 Eur/t of nutrient, i.e., a fraction (50%) of the correspondent chemical fertilizer costs [81]. No slurry treatment technologies have been considered; however, in perspective, further dewatering, drying and pelletizing treatments could be introduced in order to process the slurry and achieve an higher value product for retail markets and lower transportation requirements.

Table 8
Feed-in tariff for different plant sizes and configurations (Eur/MW h) [3].

Case study	50 kW	125 kW	250 kW	500 kW	1 MW
A	266	266	**266**	236	208
B	296	296	**296**	266	238
C	276	276	**306**	276	248
D	306	306	**336**	306	278

6.3. Further supporting measures

The main incentive available for biogas power plants with size below 1 MWe is the feed-in tariff, which can be selected by the plant owner as an alternative to the Green Certificate System [3]. The feed-in tariff option is suitable for power plants that feed their electricity into the grid, instead of self-consumption plants, because the incentive is only recognized for power sold to the grid and not for on site generation. The current Italian legislation states that the value of feed-in tariff should be revised each 3 years, even if it remains fix during the 20 years of subsidy duration. The Italian legislation allows cumulating the feed-in tariff with capital grants up to a maximum of 40% of the investment costs [2]. Specific measures of Regional Rural Development Plans provide incentives for small-scale biomass power plants, including biomass supply chains investments and heat delivery equipment. However, in this study no capital grants are considered. Another measure recently introduced by the Italian legislation to facilitate the diversification of agricultural investments and favourite the integration of bioenergy in rural areas is the assimilation of profits generated by renewable energy sales to those ones produced by agricultural activity in terms of taxation level. In particular, the agricultural profits are subject to a reduced taxation level, that can be extended to the revenues from the operation of an anaerobic digestion CHP plant if it is owned by a consortium of farmers and at least 51% of the biomass consumed by the plant is produced by the consortium itself [82].

7. Results and discussion

7.1. Energy potentials results

For each power plant size, the cases of only cattle manure feedstock ($\beta=0$), 10% of cattle farms sowable land use for energy cropping ($\beta=10\%$) and 30% of cattle farms sowable land use for energy cropping ($\beta=30\%$) are considered. The plant sizes are labelled with progressive numbers from 1 to 5, starting with the lowest size.

Table 9 summarizes the number of power plants that could be installed in each municipality and for each size and feedstock mix.

Table 9
Number of biogas plant in each Municipality for the different plant sizes and feedstocks typologies, including cumulative power and electricity fed into the grid.

Plant type	Turi	Castellana	Putignano	Gioia	Alberobello	Noci	Sammichele	Total	Power (MW)	Electricity (GW h/yr)
1_0	2	3	14	27	2	23	0	71	3.55	24
1_10	3	4	20	39	3	33	1	103	5.15	35
1_30	5	6	32	63	6	53	1	166	8.30	57
2_0	1	1	6	11	1	10	0	30	3.75	25
2_10	1	2	9	17	1	14	0	44	5.51	37
2_30	2	3	14	27	2	23	1	72	9.0	60
3_0	0	1	3	6	0	5	0	15	3.75	27
3_10	1	1	4	8	1	7	0	22	5.50	39
3_30	1	1	7	14	1	12	0	36	9.00	64
4_0	0	0	2	3	0	3	0	8	4.00	28
4_10	0	1	2	4	0	4	0	11	5.50	39
4_30	0	1	4	7	0	6	0	18	9.00	63
5_0	0	0	1	2	0	1	0	4	4.00	29
5_10	0	0	1	2	0	2	0	5	5.00	36
5_30	0	1	2	3	0	3	0	9	9.00	65

The input values of ABU_M and UAS_M used in the calculations are those ones reported in Table 2 for each municipality, and the coefficient α of 60% is assumed, as reported in Table 3. The cumulative power and electricity fed into the grid for the different plant sizes is also reported. As can be seen, most of the potentials are concentrated in three Municipalities, and the increase of cumulative electricity generated from the smallest to the largest biogas plant size is about 16%; this is due to the increased conversion efficiency of largest plants, and the higher operating hours. The results show that about 24–29 GW h_e/yr could be generated by biogas power plants fed by the manure produced in the area of study, and a number of plants ranging between 71 (50 kW size) and 4 (1 MW size) could be installed. In the case of co-digestion of manure and energy crops, with a penetration percentage of 10%, about 35–36 GW h/yr of electricity could be fed into the grid, and the number of installable plants ranges between 103 and 5; in the case of penetration percentage of 30%, about 57–65 GW h/yr of electricity could be fed into the grid, and the number of installable plants ranges between 166 and 9.

Table 10
Mass and energy flows for the selected biogas power plants.

Plant type	ABUs/yr	Haul distance d_i (km)	Average number of farms n_i	Land for energy crops (ha/yr)	Electricity (GW h/yr)
1_0	350	3.5	**11**	0	0.333
1_10	242	2.9	**8**	15	0.335
1_30	151	2.3	**5**	28	0.340
2_0	820	5.3	**25**	0	0.838
2_10	566	4.4	**18**	34	0.844
2_30	344	3.4	**11**	63	0.837
3_0	1,650	7.6	**51**	0	1.775
3_10	1,139	6.3	**35**	69	1.787
3_30	693	4.9	**22**	127	1.787
4_0	3,100	10.3	**96**	0	3.500
4_10	2,201	8.7	**68**	134	3.513
4_30	1,333	6.8	**41**	244	3.510
5_0	6,050	14.5	**188**	0	7.153
5_10	4,296	12.2	**133**	262	7.181
5_30	2,602	8.2	**61**	476	7.174

In Table 10, the mass and energy balances for each plant type are reported, considering average values of ABU_M and UAS_M for the whole area of study. The results show that, because of the biomass dispersion over the territory and the low size of the farms (32 ABU/farm on average), even considering an high cattle manure recovery percentage (α=60%), the average number of farms n_i required to feed large scale plants (size 500 kW and 1 MW) is particularly high, which is a major logistic and managing drawback; this value could be reduced in case of integration with energy crops.

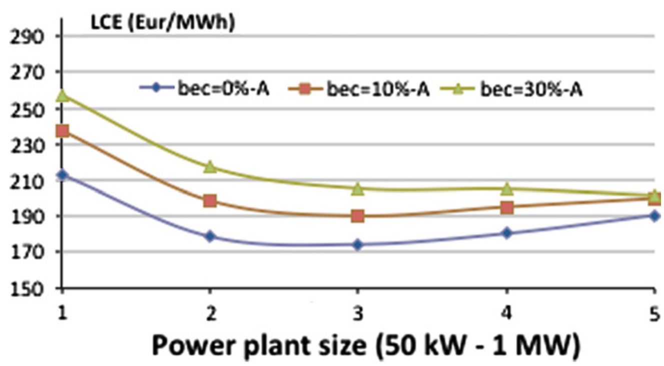

Fig. 5. Levelized cost of energy (Eur/MW h) for the different plant sizes and feedstocks mix.

7.2. Economic assessment results

In Figs. 5 and 6, the *LCE* (scenario A) and *IRR* of the investments in all the scenarios are reported. Moreover, in Fig. 7 the IRR for scenario A and C-i is reported, as a function of the number of farms required per plant n_i. Finally, in Fig. 8 the cumulative NPV of the investments is reported, for the whole area of study, considering for each plant size the number of plants and feedstock mixes reported in Table 9.

The following main conclusions can be drawn:

– The option of only manure presents a lower *LCE* and higher *IRR* at constant power plant size, on respect to the integration of triticale, and this is due to the higher supply cost of energy crops; when increasing the size, however, the difference of *LCE*

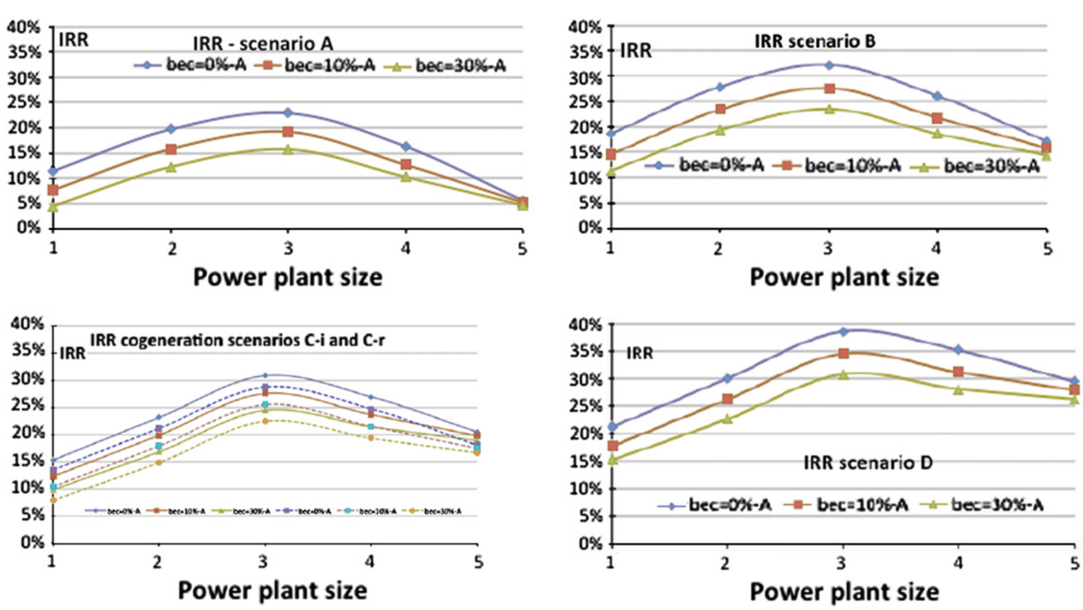

Fig. 6. *IRR* of the investment for the different plant sizes and feedstocks mix and for the four scenarios.

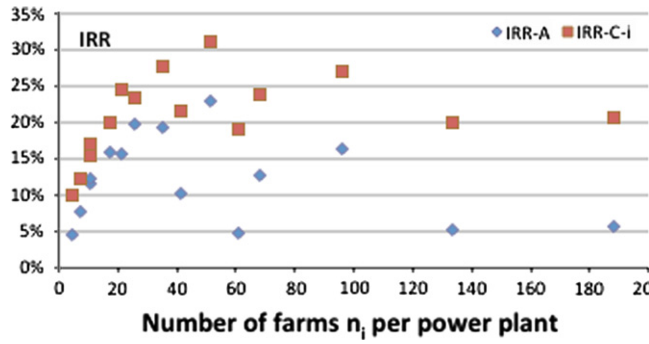

Fig. 7. *IRR* of investment for scenario A and C-i as a function of number of farms required per plant.

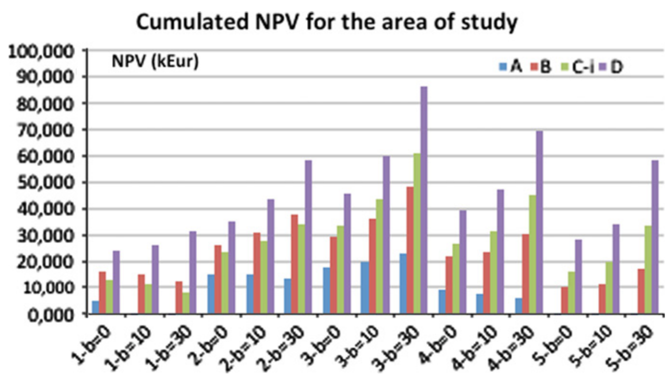

Fig. 8. Cumulative *NPV* of the investments for the whole area of study.

and (more slightly) of *IRR* among the different feedstock mixes becomes lower, because of the influence of biomass transport costs;

- At constant feedstock mix, the *LCE* fast decreases from 50 kW to 125 kW size, while at greater size the *LCE* is more constant and presents a minimum value correspondent to 250 kW size. This is mainly due to the trade-off between the increase of specific biomass supply costs (due to higher haul distances) and scale economies for larger plants. Moreover, this effect is more evident in case of low biomass density over the territory, while the the use of energy crops reduces the haul distances, so increasing the relative profitability of larger plants;
- The profitability increases from 50 kW to 250 kW size, presenting a maximum for size of 250 kW and decreasing for larger size; this is due both to the previously mentioned trade-off between haul distance and scale economies, and to the decreasing feed-in tariffs at larger sizes (see Table 8);
- The biogas slurry sale highly increases the *IRR* in all the cases, hence an acceptable profitability can be achieved also for the smallest size; the use of digestate for agronomic applications is thus a key element to improve the economic feasibility of these investments, but also to increase the environmental performances, since the use of fertilizers in agriculture can be reduced; moreover, as already discussed, in the area of study the manure is currently spread over the agricultural soil as fertilizer, thus the agronomic recovery of the slurry produced by the AD plant in the same farms could facilitate the withdrawal of the manure itself.
- The cogeneration option has different effects in case of agro-industrial or residential loads; because of the higher thermal energy utilization factor of the agro-industrial case (C-i) the profitability is increased in comparison to scenario A, and this is valid in particular for larger size plants and for higher energy crops penetrations; however, one of the main issues is, in this case, the availability of thermal energy loads with quite constant demand patterns. On the contrary, in case of residential loads the low heat factor and the heat distribution and exchanger investment costs make this option less profitable than scenario A, even assuming higher thermal energy selling price;
- The highest profitability is achieved in scenario D, when electricity, biogas slurry and heat for agro-industrial demand are sold; an IRR of 21% for 50 kW scale and only cattle manure feedstock is achieved, while 1 MW plant presents IRR in the range of 26–29% (according to the energy crops penetration rate); the most profitable size of 250 kW presents an IRR range of 30–38%;
- The use of energy crops is interesting for minimum plant scale of 250 kW, where the profitability remains higher than 26% even at triticale penetration rates of 30%;
- The analysis of the cumulative NPV for the whole area of investigation, plant sizes and feedstock mixes, shows that the maximum NPV is obtained for the plant size of 250 kW and the highest energy crops penetration rate (30%) since this configuration allows maximizing the installed power over the area of study (36 plants and 64 GW h/yr);

7.3. Sensitivity assessment

7.3.1. Influence of cattle manure rate of recovery and withdrawal price

The cattle manure rate of recovery α is a key factor for the profitability of the investment and for the selection of optimal size and feedstock mix. In fact, as reported in Fig. 9, when a manure recovery rate α of 25% is assumed, which is the current situation for the area of study, the *IRR* is very low, and it increases with the energy crops penetration rate. In this case, the use of energy crops with a penetration rate β of 30% and the optimal plant size of 250 kW is mandatory to achieve a profitability higher than 8%; on the contrary, the other plant sizes have very low or negative profitability, even in the case of 30% energy crops use. Moreover, because of the scarcity of cattle manure availability over the territory, operating a plant only with this substrate is not profitable for each plant size, and an integration with energy crops is required. When the manure recovery rate is 40%, the *IRR* is not influenced by the feedstock mix; however, relevant differences arise in terms of logistic and managing aspects of the supply chain, that could make easier the use of energy crops to reduce the number of cattle farms n_i and the hauling distance d_i. With manure recovery rates of 60% (as assumed in the previous

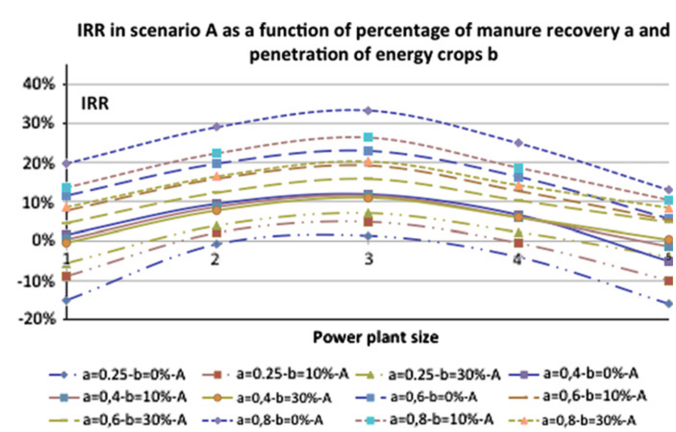

Fig. 9. *IRR* for the scenario A and different plant sizes with percentage of manure recovery (α) varying between 25% and 80%, and for different energy crops penetration scenarios (β).

simulations) or higher, the use of only manure becomes more profitable than the integration with energy crops, and the *IRR* of the investments strongly increases. It is clear that one of the key factors to achieve an high profitability of these investments is thus the possibility to increase the rate of manure recovery from the cattle farms and, when this rate is lower than 40%, the integration of energy crops can be an option to increase the investment profitability of the plants.

The manure recovery rate can also be related to its withdrawal price, since higher prices could stimulate the recovery. For this purpose, the *IRR* as a function of manure recovery rate (ranging between 25% and 80%) is reported in Fig. 10, with manure withdrawal price (c_m) varying between 0 Eur/t and 7 Eur/t. The graph is referred to scenario A and power plant size of 250 kW. The dotted lines represent the case of 30% energy crops penetration. As can be seen, the highest profitability is achieved at high manure recovery rates with only manure feedstock. Moreover, with a recovery rate of 58%, a similar profitability can be achieved with only manure feedstock and withdrawal price of 7 Eur/t or 30% energy crops with free manure withdrawal price. It also results that, in case of only manure feedstock, it is more profitable to achieve 80% manure recovery rate with *cm* equal to 7 Eur/t than 40% recovery rate and free manure withdrawal.

7.3.2. Influence of cattle farms parameters

The distribution of the biomass resource over the territory, and in particular the cattle farms density, influences the investment profitability and the selection of optimal plant size and feedstock mix. As an example, Fig. 11 reports the results of the *LCE* in scenario A and with the parameters (ABU_M, UAS_M and ρ_{farm}) of the Municipalities of Noci and Sammichele, respectively (reported in Table 2). It can be seen that the very low cattle farm density of the Municipality of Sammichele (0.36 farms/km^2, see dotted line in Fig. 11) determines higher *LCE* in comparison to Noci, and this effect is augmented at larger plant scale. As a result, the minimum *LCE* for the Municipality of Sammichele is correspondent to plant size of 125 kW. Moreover, as in the case of low cattle manure rate of recovery, the low cattle farms density makes the use of energy crops more competitive than only manure, but only at larger plant size (500 kW or 1 MW).

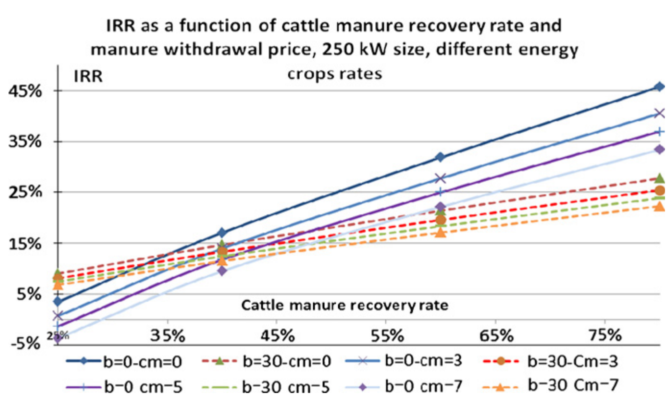

Fig. 10. Variation of *IRR* for 250 kW plant size and scenario A as a function of cattle manure recovery rate (*x* axis) and manure withdrawal price (*cm*). Dotted lines represent the case of 30% energy crops rate, continues lines represent the case of 0% energy crop rate.

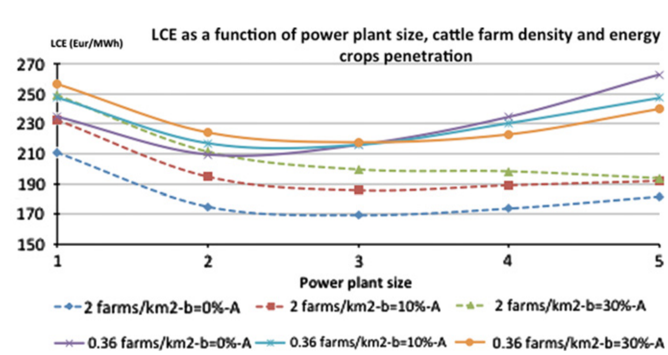

Fig. 11. *LCE* for the scenario A and different plant sizes and energy crops penetration, in case of Municipality of Noci (ρ_{farm}=2 farms/km^2) and Sammichele (ρ_{farm}=0.36 farms/km^2) (dotted line).

8. Conclusions

The research proposes an approach to estimate the potentials of manure and energy crops for a given territory and applies the methodology to the area of the LAG "Terra dei Trulli e del Barsento", Province of Bari. For this purpose, 774 cattle farms have been assessed, covering about 68% of the total farms of the Province of Bari. The results show that the average farm's size is quite small, with about 32 ABU/farm and a total number of 24,000 ABU in the territory. Most of the farms are located in the Municipalities of Gioia del Colle (38%), Noci (32%) and Putignano (19%). The breeding technique is in most cases a free-type, where the bovines graze into the agricultural areas of farm and stand in the cowshed during the night or for milking.

Cattle manure is the main animal waste produced in the area, and the results of structured interviews show that about 26% of the manure produced is currently recovered by the farmers, because of the breeding techniques that determine a dispersion of the resource over the territory. With the hypotheses of an efficient manure supply chain, and considering a manure withdrawal price for energy conversion that offers a profitability for the farmer, a level of manure recovery of about 60% could be reasonable, which corresponds to about 9.5 t manure/ABU year (while this value is currently 4.1). With these assumptions, about 236,000 t manure/year could be available for anaerobic digestion in the LAG territory, corresponding to 89 GW h/year of primary energy. The further option of energy crops (triticale) cultivation in the same cattle farm's sowable land to integrate the power plants feedstock is explored, with a percentage of 10% and 30% of farm's sowable land reconversion, which corresponds respectively to 1500 ha/yr and 4500 ha/yr. The energy potentials assessment report a cumulative power that could be installed in the area of study, respectively, of 3.5 MW, 5.1 MW and 8.3 MW in the case of small power plants (50 kW) fed by cattle manure or a mix with energy crops (10% and 30%). These values become, respectively, 4 MW, 5 MW and 9 MW in the case of large plants (1 MW).

The profitability assessment, carried out assuming the Italian feed-in tariff subsidies for biogas plants, reports, for a baseline scenario of only electricity sale and only manure feedstock, a maximum *IRR* (22.9%) correspondent to 250 kW. In this case, the number of cattle farms required to feed the plant is about 50. The profitability of energy crops integration is strictly related to the manure recovery rate and cattle farms density over the territory; in particular, when the manure rate is below 40% (at manure withdrawal price of 3 Eur/t) the integration with energy crops is more profitable than the option of only manure, and this percentage becomes about 30% if the manure withdrawal is free.

In conclusion, with the feed-in tariffs available in Italy for biogas power plants, and on the basis of the characteristics of the cattle farm sector in the area of study, the biogas power plant investments are profitable if the cattle manure recovery rate is higher than 25%. In this case, the option of only manure feedstock is more profitable than the integration with energy crops. The results indicate that, at high biomass resource dispersion levels, the long distance transport of low energy density biomass is not

feasible and the bioenergy plants will be constrained in scale. The optimal size will be the trade-off among increasing feedstock transport cost, decreasing plant capital and operation costs and other factors such as the variations in the cost to access power grid, as the plant size increases. Strategies to improve plant profitability include: (a) locating the plant near the areas of high feedstock production density (i.e., clusters with "anchor" cattle farms); (b) integrating biomass transport into the business of either biomass producers or power plant operators, to reduce the related costs; (c) encouraging farmers to increase the manure recovery rate, with a biomass withdrawal price; (d) gaining further income from the biogas slurry sale as fertilizer (and this could make profitable also smaller scale plants and/or low manure recovery rates); (e) locating the power plants near to heat demand, in particular with constant demand patterns such as for agro-industrial loads, in order to use the excess thermal energy produced by the cogeneration plants; (f) integrating the power plants into cattle farms, in particular in case of small scale plants, in order to reduce operational costs; (g) exploring the possibility of co-digestion with other fermentable bio-wastes from agricultural and agro-industrial sector, that could integrate the power plant's feedstocks.

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